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Developing a Nationally Appropriate Mitigation Measure from the greenhouse gas GHG abatement potential from livestock production in the Brazilian *Cerrado*

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Abstract

Brazil is one of the first major developing countries to commit to a national greenhouse gas (GHG) emissions target that requires a reduction of between 36.1% and 38.9% relative to baseline emissions by 2020. The country intends to submit agricultural emissions reductions as part of this target, with livestock production identified as offering significant abatement potential. Focusing on the *Cerrado* core (central Brazilian savannah), this paper investigates the cost-effectiveness of this potential, which involves some consideration of both the private and social costs and benefits (e.g. including avoided deforestation) arising from specific mitigation measures that may form part of Brazil's definition of Nationally Appropriate Mitigation Measures (NAMAs). The analysis used an optimization model to define abatement costs. A baseline projection suggests that beef production in the region will emit 2.6 Gt CO_2e (CO2 equivalent) from 2010 to 2030, corresponding to 9% of national emissions (including energy, transport, waste, livestock and agriculture). By implementing negative-cost measures identified in a marginal abatement cost curve (MACC) by 2030, the 2.6 Gt CO_2e could be reduced by around 24%. Pasture restoration, involving avoided deforestation, offers the largest contribution to these results. As the Brazilian *Cerrado* is seen as model for transforming other global savannahs, the results offer a significant contribution by identifying alternatives for increasing productivity whilst minimizing national and global external costs.

Keywords: climate change; marginal abatement cost curves; mitigation measures; sustainable intensification; grassland restoration; linear programming.

Highlights

- Around 66% of beef production emissions in the *Cerrado* are due to enteric fermentation.
- 24% of emissions can be reduced by adopting negative-cost (cost-saving) measures.
- Pasture restoration has the biggest abatement potential (27.8 Mt $CO_2e.yr^{-1}$).

1. Introduction

Global demand for livestock products is projected to grow by 70% by 2050 (Gerber et al., 2013). This is expected to generate significant additional pressure on producers and on natural resources. Sustainable management (or intensification) will require increasing yields and efficiency in existing ruminant production systems, minimizing competition of land used for food and feed, while maximizing ecosystem services, including mitigation of greenhouse gas (GHG) emissions (Gerber et al., 2013; Soussana et al., 2013; Thornton and Herrero, 2010).

Tropical regions are implicated as potentially offering major opportunities to increase beef productivity and emissions mitigation, as current productivity levels are still relatively low and emission intensities correspondingly high (Opio et al.,2013; Gerber et al., 2013).

More productive pastures can increase soil carbon stocks, providing one of the largest terrestrial carbon sinks (Follett and Reed, 2010; Neely et al., 2009), in a pool that is a more stable form than the aerial components of forests (Soussana et al., 2010). But potential carbon sequestration in soils under grasslands far from offsets the loss of above ground vegetation in the majority of tropical areas, and therefore natural vegetation should be preserved.

Brazil is the world's second largest beef producer – 9.3 $Mt.yr^{-1}$ (14.7% of the world's total), and the largest exporter in 2012-13 (FAO, 2014). Production is predominantly pasture-based in a grassland area of approximately 170 Mha (IBGE, 2014), mostly in a humid or sub-humid tropical climate.

But beef production can entail significant trade-offs, that must be managed to minimize external costs. These include the controlled expansion of agricultural area, associated deforestation, cost-effective greenhouse gas mitigation, and land competition between food and biofuels.

Analysis of historical data (Martha et al., 2012) and scenario studies conducted by the World Bank (Gouvello et al., 2011) suggest that improving beef productivity has the highest potential to buffer the expansion of other agricultural activities, avoiding further deforestation. Increasing pasture productivity can also boost soil carbon sequestration, particularly when carried out in currently degraded grasslands (Braz et al., 2013; Ruviaro et al., 2014). In addition, increasing productivity through feed supplementation may significantly reduce direct methane emissions (Berndt and Tomkins, 2013; Ruviaro et al., 2014).

In this context and based on its previous National Plan on Climate Change, at the Conference of the Parties 15 (COP 15), Brazil has proposed Nationally Appropriate Mitigation Actions (NAMAs) as part of its commitment to the United Nations Framework Convention on Climate Change (http://www.mmechanisms.org/e/namainfo/index.html). Over the period 2010-2020, the NAMAs establish targets for the reduction of Amazon deforestation by 80% and by 40% in the *Cerrado* (Brazilian Savannah), through the adoption of pasture recovery (15 Mha), and from integrated crop-livestock-forestry systems (4 Mha). With these cattle-related measures, Brazil expects to reduce net emissions by between 101 and 126 Mt CO_2-e, by 2020, which account for 61% - 73% of all mitigation in agricultural practices by the NAMA route. The NAMA proposal is enacted as part of the ambitious ABC (Agricultura de Baixo Carbono - Low Carbon

Agriculture) program, which offers low interest credit lines to farmers adopting mitigation technologies (Mozzer, 2011).

This paper investigates the cost-effectiveness of key livestock mitigation measures applicable in the *Cerrado* core (Central Brazilian Savannah); a region that contains around 35% of the Brazilian herd (Anualpec, 2010). The region is considered as central in Brazil's ascendance in global production (The Economist, 2010; The New York Times, 2007) and is still regarded as the most important region for expanding beef production in Brazil (Ferraz and Felício, 2010). It is seen as a potential model for transforming other savannahs (Morris et al., 2012).

The analytical focus is significant because there is currently little research clearly demonstrating that mitigation through livestock management can be delivered at relatively low cost. The paper offers the first bottom-up cost-effectiveness analysis using an optimization model for Brazilian beef production. The measures evaluated are pasture restoration, feedlot finishing, supplement concentrates and protein and nitrification inhibitors. The analysis uses the outputs of a multi-period linear programming model (See Appendix S1) to develop a bottom-up or engineering marginal abatement cost curve (MACC), to represent the relative cost-effectiveness of measures and their cumulative abatement potential above a baseline of business as usual (Moran et al., 2010). The analysis examines the direct emissions reductions attributable to measures enacted within the notional farm gate rather than wider life cycle impacts (i.e., post farm gate), and accounts for both the private and social costs and benefits (e.g. including avoided deforestation).

The paper offers new insights for regional policy and is structured as follows. Section 2 outlines the modelling structure and relevant optimization assumptions underlying the cost-effectiveness analysis. Section 3 describes the MACC calculation, while section 4 sets out results. Sections 5 and 6 offer a discussion and conclusions.

2. Modelling methods for mitigation cost-effectiveness

2.1 Model Overview

Abatement potential and cost-effectiveness of measures were derived using a multi-period linear programming model (See Appendix S1 for detailed mathematical description) that simulates a whole cycle (cow-calf, stocking and finishing) beef production farm, accounting for: (i) herd dynamics, (ii) financial resources, (iii) feed budgeting, (iv) land use: pasture recovery dynamics and crops, and (v) soil carbon stock dynamics.

The model optimizes the use of the farm resources (capital, cattle, land) while meeting demand projections and maximizing profit. In this context the model is used to simulate beef production treating the *Cerrado* region as a single farm. The farm activities (i-iii) are modelled using monthly time steps, while (iv & v) are modelled using annual time steps. The model represents animals in age cohorts k; a steer of age cohort $k=1$, is a calf aged 6 months, and 189 kg of live weight (LW). After 3 months in the system, age cohort k is transferred to age cohort $k+1$, now with 222 kg of LW. The final weight is 454 kg, corresponding to $k=9$ (33 months), when the animal is sold and removed from the system.

The same cohorts apply to heifers, although these can also accommodate breeding rates, where a heifer generates 1 calf per 18 month cycle, comprising 9 months of pregnancy, 6 months of lactation (Millen et al., 2011), plus 3 months of non-lactation and non-pregnancy. Half of the calves born are allocated to steers and the other half are allocated to heifers, both of age cohort $k=1$. After 4 cycles, the cows are removed from the system and slaughtered, i.e., used to meet demand.

The model also simulates feedlot finishing, and thus allows the reduction of the finishing time. It can remove a proportion of steers from exclusive grazing, inserting the animals into feedlot systems; generally only males are confined in Brazil (Millen et al., 2009; Costa Junior et al., 2013). For all cattle categories, i.e., male, female, male in feedlot and breeding females, the corresponding age cohort is associated with specific parameters: weight, mortality rate, dry matter (DM) intake, selling and purchase prices, emissions factors for CH_4 from enteric fermentation and emissions factors for N_2O from excreta. The associated coefficient values are detailed in Table S1 and Table S2.

The gross margin of the *Cerrado* single region farm is maximized and calculated as the difference between the income and expenses. Income derives exclusively from the sale of finished cattle, 454 kg of LW for steers and 372 kg of LW for heifers. Farm expenses are composed of investment and maintenance costs. Maintenance costs are (i) farm maintenance and (ii) animal non-feed maintenance. Costs for (i) include working animals, machinery and equipment, veterinary equipment, telephone device, fuel, taxes and fees, totalling US$ 25.00 $ha^{-1}.yr^{-1}$ (See Table S8 details). Costs for (ii) were calculated for each age cohort and it is composed of cost of mineral salt and expenses with health (vaccines), and animal identification (Table S1).

2.2 Land use dynamics

The model simulates land use dynamics by allocating the total area across pastures or crops; the latter being used for grain and silage production to be used for the formulation of ration for feedlot and supplementation for grazing cattle. The model allocates land into pasture, soybean and corn. In the case of pasture, the model allocates land into different productivity levels. Pasture degradation and restoration rates are key model processes that have a bearing on overall system productivity and hence emissions intensity of production.

2.2.1 Grassland degradation

Pasture degradation can be defined as the loss of vigour and productivity of forage. To represent the degradation process, we define six levels of Dry Matter Productivity (DMP): *A*, *B*, *C*, *D*, and *F* (Table 1), where level *A* is the pasture of highest productivity, and level *F* is fully degraded. If no action is taken to maintain or improve productivity of a fraction of the area in a given level, it is relocated to a lower productivity level. So, after a period of time (assumed as two years herein) category *A* degrades to category *B*, *B* degrades to *C*, and so on, until pasture *F*, thus completing a 10 years full degradation (with no management interventions).

The DMP of the pastures levels were calculated exogenously using a model that estimates seasonal pasture growth according to soil, species and climate conditions (Tonato et al, 2010). Each pasture level of DMP is associated with a carbon equilibrium value that is used to estimate changes in soil organic carbon due to pasture management (see section 2.3 for details).

Table 1: Annual dry matter productivity and equilibrium C stock values in function of land use.

Land use	DM[1] ($t.ha^{-1}.yr^{-1}$)	Soil carbon stock equilibrium[2] ($t.ha^{-1}$)
Pasture A	19.6	84.3
Pasture B	17.6	82.7
Pasture C	12.6	62.3
Pasture D	8.7	45.2
Pasture E	5.8	32.4
Pasture F	3.9	26.1
Corn (Silage)	9.0	45.0
Corn (Grain)	3.8	40.0
Soybean	2.5	45.0

[1] Estimated using the model published by Tonato et al. (2010)

[2] According to Parton (1987)

2.2.2 Land use change and pasture restoration

To offset the degradation process the model can allow for grassland restoration through improved forage quality by direct restoration (by chemical and mechanical treatment) or indirect restoration (by rotating with crops). For example, in a given year a pasture *A* will degrade to *B*, the optimal solution might be letting half of pasture *A* to degrade, and half be maintained to level *A*. Furthermore, the model works simultaneously with a composition of pasture DMP levels; e.g., in a given year *t*, the composition can be 4% of *A*, 10 % of *B*, 85% of *C*, and 1% of soybean. Then, at year *t+1*, the composition can change by any combination among the pasture DMP levels and crops.

For each type of land use change or restoration, there is an associated cost (Table 2). Costs were calculated accounting for the amount of inputs and services (e.g., nitrogen, limestone, micronutrients, forage seeds, internal transport) needed to maintain or increase the DMP level in the target pasture DMP level. For details of applied inputs, see Table S3-S7 in Appendix S3.

Table 2: Costs of pasture restoration practices and crops planting. The table can be read as “the cost to restore one hectare of pasture “*X*” to an improved pasture “*Y*”, or in some cases, “the cost to move one hectare from land use “*X*” to land use “*Y*”, where “*X*” and “*Y*” are any element in the column “Pasture/Crop”. The case of *X*=*Y* (table diagonal), represents the cost of maintaining a given pasture at the current DMP level (i.e., cost of avoiding degradation) or the cost of replant a crop in the same area.

	Costs of pasture restoration practices/land use change[1] (US$2012.ha-1)								
Land use	Pasture A	Pasture B	Pasture C	Pasture D	Pasture D	Pasture F	Corn (Silage)	Corn (Grain)	Soybean
Pasture A	112.4	0.0	0.0	0.0	0.0	0.0	1352.6	600.0	345.4
Pasture B	149.9	72.7	0.0	0.0	0.0	0.0	1502.5	749.9	495.3
Pasture C	399.3	249.4	15.0	0.0	0.0	0.0	1751.9	999.3	744.7
Pasture D	630.0	480.0	230.7	9.4	0.0	0.0	1982.6	1229.9	975.3
Pasture D	724.6	574.6	325.2	94.6	5.6	0.0	2077.2	1324.5	1069.9
Pasture F	767.0	617.1	367.7	137.1	42.5	5.6	2119.6	1367.0	1112.4
Corn (Silage)	269.8	200.9	125.1	125.1	125.1	125.1	1630.7	1060.6	971.8
Corn (Grain)	269.8	200.9	125.1	125.1	125.1	125.1	1736.4	981.9	992.6
Soybean	269.8	200.9	125.1	125.1	125.1	125.1	1736.4	981.9	1017.7

[1] See Appendix S2 for calculation details.

Land use change (including deforestation), degrading or restoring pasture will affect the soil carbon (C) stocks. These changes are calculated by estimating the annual C stock under pasture and crops for each land use. The total accumulated C under soils is given by the sum of the C stock of each pasture DMP levels, soybean and corn.

2.3 Carbon sequestration through pasture management

Depending on the DMP, the C flux may change significantly. The model works with equilibrium values of the C stock for each type of pasture and crops. The higher the pasture productivity, the higher the C equilibrium value (Table 1). The equilibrium values were calculated exogenously, using simulations from the CENTURY model (Parton et al., 1987) applied to *Cerrado* biophysical characteristics and using the annual DMP calculated for each pasture category.

The model accounts for the annual carbon stocks per each land use in column 1, Table 1. The model transfers the accumulated carbon from year $t-1$ to year t and calculates the variation of soil C in year t.

Letting $C_{t,lu}$ be the soil carbon stock (tonnes) under the land use lu, where $lu \in \{A, B, C, D, E, F, Soybean, Corn(silage), Corn(grain)\}$. Then $C_{t,lu}$ can be expressed by:

$$C_{t,lu} = \varphi(t,lu) + \Delta C_{t,lu} \quad \text{(Eq. 1)}$$

And

$$\Delta C_{t,lu} = f(\varepsilon_{lu}, C_{t-1,lu}) \quad \text{(Eq. 2)}$$

Eq. (1) is composed of the carbon transference term, $\varphi(t,lu)$, and the C sequestration term, $\Delta C_{t,lu}$. The term φ(t,lu) accounts the transference of C from other uses to land use *lu* in year *t*; e.g., if *lu* is equal pasture *B*, and one hectare of soybean is converted in year *t* into one hectare of pasture level *B*, the carbon previously stocked under soybean has to be transferred to pasture *B*. Similarly, if some hectares are converted from pasture *B* to pasture *A*, or degraded to *C*, then part of the C stock from *B* has to be proportionally transferred from *B* to these other uses. The sequestration term, $\Delta C_{t,lu}$ is written as a function of the difference between the previous C stock $C_{t-1,lu}$, and the C stock equilibrium value, ε_{lu}. Hence the further the previous stock is from the equilibrium value, the more C will be up taken. Conversely, if due to the land use change, or degradation, the C stock becomes greater than the equilibrium value, there will be negative C sequestration, i.e., a loss of C stock. These modelling approaches follow the concepts suggested by Eggleston et al. (2006) and Vuichard et al. (2007). The extended version of Eq. (1) and (2) are presented in Appendix S1.

2.4 Deforestation due to cattle ranching

For pasture area we use the projections published by Gouvello et al. (2011) combined with an endogenous deforestation term. Let LU_t be the total area at year t; a_t the exogenous projections; and D_t the endogenous term that represents further area expansion. Then for every year:

$$LU_t = a_t + D_t \quad \text{(Eq. 3)}$$

The deforested area will cause a loss of carbon stocks in natural vegetation and influence soil C; and directly influences the transference term in eq. (1), i.e., loss of soil organic matter (SOM). Both vegetation carbon stocks and SOM are accounted to represent the emissions associated with deforestation.

There is limited quantitative research accounting for the dynamics of pasture productivity following deforestation. In accordance with the best available information, the model allocates new converted areas into the system in pasture category *C* (the highest without nitrogen fertilization), as soil carbon also can increase or decrease values after deforestation (Maia et al., 2009) and pasture productivity is relatively high after conversion due to higher soil organic matter mineralization (Martha Jr, 2007). In this analysis, we assumed the cost of opening new areas is zero because the cost of conversion the *Cerrado* into pastures can be offset by timber sales and land value appreciation (Bowman et. al, 2012).

Another assumption is that the model cannot discard land endogenously, neither does it allow fallow in any year of the planning period. This assumption is based on the fact that cattle ranchers are not allowed to let their properties be unproductive; otherwise the land can be confiscated by the government for agrarian reform (Federal Law 8.629 - www.planalto.gov.br/ccivil_03/leis/l8629.htm).

2.5 Baseline construction

Land use change scenarios need to be mapped onto a plausible baseline for land use activity. The baseline scenario is based on national forecasts of beef demand and grassland area for Brazil, from 2006 to 2030 (Gouvello et al., 2011). The assumption is that the attributable *Cerrado* pasture area and beef demand share are a fixed proportion of the national projections. In 2006, the *Cerrado* pasture area represented 34% of the national total (IBGE, 2014). The model then assumes that *Cerrado* pasture area corresponds to 34% of Brazil's pasture area, and this proportion is constant during the studied period (2006-2030). Similarly, as there is no data for regional demand, we assumed demand to be proportional to area, i.e., demand for *Cerrado* is also equivalent to 34% of national demand, this percentage is very close to the 35% figure estimated by Anualpec (2010).

In the model, increased productivity occurs by means of investments in technologies, e.g., pasture restoration, supplementation and feedlot animals. The baseline scenario has limited adoption of these measures, implying constant productivity. We assumed that pasture restoration is allowed in the baseline only to avoid degradation, but it is constrained to maintain productivity at 2006 levels (10 t-DM.ha^{-1}.yr^{-1}, as calculated in Appendix S2). Combining this constraint with projected increased demand pushes the model to open new areas if it is necessary to meet the growing demand for beef.

The current adoption rate of feedlot finishing in Brazil is around 10% of the total herd (Anualpec, 2010). We assumed this proportion to be constant in the baseline, a rate that is in counterpoint to a higher level of penetration of this measure in a mitigation counterfactual.

2.6 GHG emissions sources

The model calculates GHG emissions using emissions factors for activities within the farm gate. GHG emissions associated with the farm activities are: (a) CH_4 from cattle enteric fermentation (CH_4 from excreta is not accounted); (b) N_2O from cattle excreta; (c) N_2O direct emissions from N fertilization; (d) CO_2 from deforestation; and (e) CO_2 from pasture degradation and land use change from pasture to crops. Items (a) and (b) depend on herd composition: each age cohort of males and females (heifer or cow) has an associated emission factor of CH_4 and N_2O calculated using Tier 2 methodology (Eggleston et al., 2006), see Table S1 and Table S2. Due to the lack of studies in Brazilian conditions, for (c), we used the Tier 1 IPCC default factor of 1% (Eggleston et al., 2006). The emissions from (d) are calculated using coefficient of loss of natural vegetation per deforested area. The average carbon loss of natural vegetation due to deforestation was estimated as 34.6 tonnes of C per hectare, in accordance to Eggleston et al. (2006) and Bustamante et al. (2012). For (e), the emissions are calculated according to Eq. (1) and (2).

2.7 Mitigation Measures

The selection of GHG mitigation measures was based on literature review and expert opinion regarding the relevance and applicability of the technologies to Brazilian livestock production and conditions. The measures evaluated are: concentrate supplementation, protein supplementation, pasture restoration, nitrification inhibitors and feedlot finishing. Although the latter is already in the baseline, we investigated a higher adoption rate of this technology.

Modelling assumptions for these measures related to the effects the measures have upon the gross margin and emissions are detailed in Table 3.

Table 3: Selected livestock mitigation measures

Mitigation measure	Description	Cost[1]	Unit	Reduces emissions by:	Adoption rate target
Feedlot finishing	When cattle weight is around 80% of the slaughter weight it is removed from pasture and grass to feedlot on a diet with ration of balanced protein and energy content	9.12	$\$.head^{-1}.mth^{-1}$	Shorter animal life cycle by increasing weight gain	15% of the total finished animals.
Nitrification inhibitors	Application of Agrotain Plus® together with urea used as fertilizer; 3 g per Kg of applied nitrogen[2]	61.44	$\$.t^{-1}$	Reduced conversion of nitrogen to the GHG nitrous oxide (nitrification)	Optimized
Pasture restoration	Improving pasture forage productivity by soil chemical and mechanical treatment. As described in Section 2.1	Table 2	$\$.ha^{-1}$	Avoiding the need for additional pasture land and increasing organic carbon sequestration	Optimized
Supplementation concentrate	Feeding cattle via grazing and a ration with a high energy content. Grazing steers with 421 kg of LW can be selected for concentrate supplementation. The supplementation takes 2 months and the final weight is 490 kg	3.07	$\$.head^{-1}.mth^{-1}$	Shorter animal life cycle by increasing weight gain	Optimized
Supplementation protein	Feeding cattle via grazing and a ration with a high protein content. Calves (189 kg) can be selected (only in March) to be supplemented with protein. The steers are finished after 15 months, with 481 kg	1.15	$\$.head^{-1}.mth^{-1}$	Shorter animal life cycle by increasing weight gain	Optimized

[1] In the case of supplementations the values refer to non-feed costs, for feed costs see ration formulation (Table 4)

[2] According to manufacturer's recommendation (http://www.agrotain.com/us/home).

2.7.1 Concentrate and protein supplementation

Both measures involve supplementing the feed of grazing steers; e.g., feed is composed of forage and supplements. It is expected that these measures reduce emissions since animals gain weight faster and take less time to be finished.

Table 4: Rations (supplements) formulation and costs.

Crop	Ration Formulation (%)[1]			Cost[2] (US$.kg^{-1})
	Feedlot	Concentrate	Protein	
Corn (grain)	83	80	15	PBF
Corn (Silage)	11	0	0	PBF
Soybean	5	17	39	PBF
Urea	0	2	12	1.19
Mineral Salt	1	1	19	0.84
NaCl	0	0	15	1.19

[1] Rations were formulated by using the software Invernada (minimum cost ration formulator) (Barioni, 2011)

[2] PBF = Produced by the farm, i.e., corn and soybean are not purchased but produced endogenously in the model.

Biological coefficients, e.g., mortality rate, weight, DM intake, and emissions factor for steers fed with supplementations can be found in Table S2.

2.7.2 Pasture restoration

This measure works in the model by avoiding deforestation and because restoration boosts carbon soil uptake. Details of the modelling and costs are explained in section 2.2.2. In contrast to the baseline scenario, to evaluate this measure, the fixed DMP baseline constraint was removed.

2.7.3 Nitrification Inhibitors

The measure works by avoiding a proportion of the N in fertilizer or manure being converted into N_2O, i.e. nitrification and denitrification process (Abbasi and Adams, 2000). To date there have been no studies detailing the reduction in N_2O emissions for Brazilian pastures when nitrogen inhibitors are applied. A 50% reduction of direct N_2O emissions is assumed in this paper - as found by Giltrap et al. (2011) for a New Zealand study. We assumed that this measure is applicable only over the N used for pasture and crops fertilization. The reason is that most of the Brazilian herd is based on a grazing system where it is unfeasible to apply inhibitors to animal excreta.

2.7.4 Feedlot finishing

Like supplementation, this measure works by reducing the cattle finishing time since feedlot animals are fed only by ration (with the formulation described in Table 4). Only steers can be selected to model in the feedlot system. The adoption rate was arbitrarily assumed to be 15% of the total finished herd, since in the baseline the adoption rate is 10% of the total finished herd, the measure can be stated as: increasing by 50% over the baseline adoption rate.

3.1 Marginal abatement cost curve

A MACC can be used to represent the relative cost-effectiveness of different abatement options and the total amount of GHG that can be abated by applying mitigation measures over and above a baseline scenario. The aim is to identify the most economically efficient manner to achieve emissions reduction targets, where the cheapest units of greenhouse gas should be abated first (Moran et al., 2010).

MACC analysis can be derived by means of a top-down analysis – which usually makes use of a general equilibrium model and emissions are calculated endogenously, or by a bottom-up or engineering analysis (MacLeod et al., 2010). This paper takes a bottom-up approach, where the individual abatement potential of measures and their costs are individually modelled.

The MACC can be presented in form of a histogram, where the C abatement potential lies on the x-axis, and the cost per tonnes of abatement in the y-axis. The abatement potential of a measure *m* (AP_m) is calculated as the annual average of the difference between the business-as-usual (baseline) total GHG emissions (E_{BAU}) and the total emissions under the mitigation measure scenario (E_m) during the production period *T*:

$$AP_m = \frac{E_{BAU} - E_m}{T} \quad \text{(Eq. 4)}$$

The cost-effectiveness of measure *m* (CE_m), therefore, is calculated by:

$$CE_m = \frac{GM_{BAU} - GM_m}{AP_m} \quad \text{(Eq. 5)}$$

Where GM_{BAU} and GM_m are, respectively, the gross margin in the baseline scenario and the gross margin in the scenario with the measure *m* implemented.

As observed in Eq.4 and Eq.5, AP_m and CE_m are average values across the planning period.

4. Results

4.1 Baseline Emissions

In the baseline scenario, beef production in the *Cerrado* accounts for an average of 121.5 Mt $CO_2e.yr^{-1}$, from 2010 to 2030. This value includes enteric fermentation, animal waste (emissions from excreta), soil fertilization emissions, pasture (due to the loss in C stocks), and deforestation driven by cattle production (Fig. 1). The accumulated emissions from 2010 to 2020 account for about 1,249 Mt CO_2e or 2,551 Mt CO_2e from 2010 to 2030.

In relative terms, enteric fermentation makes the biggest contribution to the total: 66% of emissions, followed by deforestation, with 26%. The results also show that pasture degradation is a considerable source of emissions, accounting for an average of 8.35 Mt $CO_2e.yr^{-1}$ (an average of 0.06 t $CO_2e.ha^{-1}.yr^{-1}$), the equivalent to 4% of emissions or the same proportion as animal waste (Fig. 2).

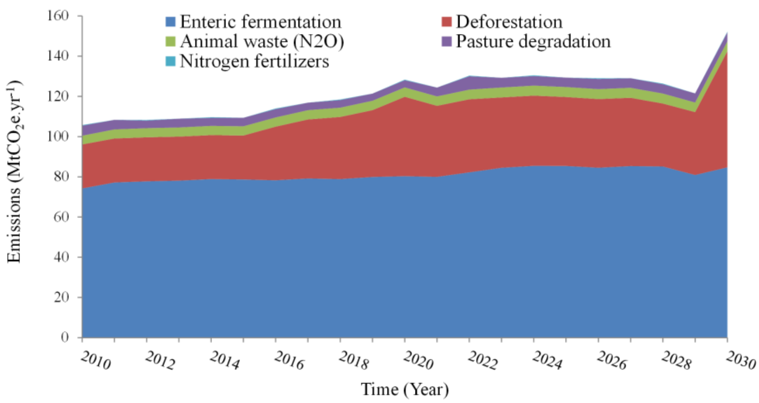

Figure 1: Baseline emissions of beef production in the Brazilian *Cerrado* for the 2010-2030 period according to: nitrogen fertilizer (appplied to pastures restoration and crops plantation), animal waste (cattle direct N_2O emissions through excreta), pasture degradation (loss of soil organic carbon) and deforestation (loss of above ground organic carbon).

Gouvello et al. (2011) suggests that total national GHG emissions from energy, transport, waste, livestock and agriculture, will be around 1.70 Gt CO_2e by 2030. The results presented here suggest that beef production in the *Cerrado* will be responsible for about 152 Mt CO_2e in 2030, corresponding to 9% of total national GHG emissions.

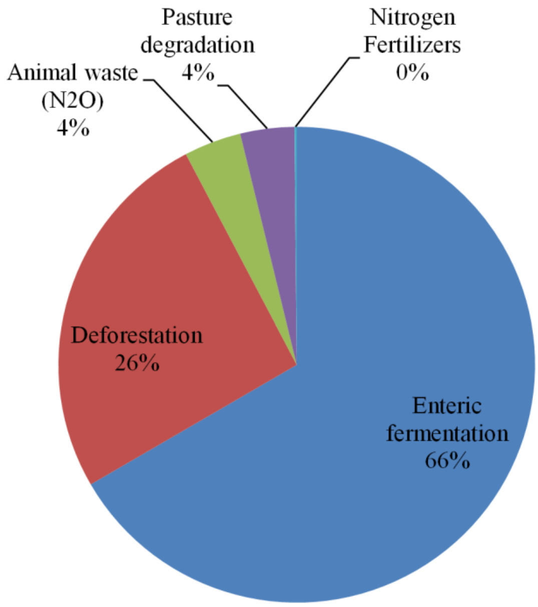

Figure 2: Share of the main GHG emissions sources from beef production in the Brazilian *Cerrado*. The values relates to the proportion of each source in relation to the accumulated emissions for the period 2010-2030.

In the baseline scenario, without increasing productivity, an average deforestation rate of 246.1 10^3 $ha.yr^{-1}$ would be required to meet the beef demand projections.

Emissions attributed to the use of fertilizers were not significant, accounting for an average of 0.2 Mt $CO_2e.yr^{-1}$. This was expected, since small amounts of N are used to fertilize *Cerrado* pasture soils (Martha Jr et al., 2007; Cederberg et al, 2009).

4.2 Cost-effectiveness analysis

For policy purposes it is important to detail the relative cost of emissions mitigation measures. Three of the five mitigation measures simulated, - concentrate supplementation, protein supplementation, and pasture restoration - have negative cost-effectiveness: US$-8.01. t CO_2e^{-1}, US$-2.88. t CO_2e^{-1} and US$-0.05. t CO_2e^{-1}, respectively (Figure 3). Adopting these measures implies cost savings while reducing emissions. These measures work by balancing the loss of DM production during the dry months. The *Cerrado* biome is predominantly seasonal tropical, meaning dry winters and rainy summers, with lower pasture productivity during the dry months. If cattle are supplemented with concentrates or protein they can be finished earlier, thereby reducing emissions.

Due to the large applicable area (approximately 60 Mha), and given the current low productivity of 10 t $DM.ha^{-1}.yr^{-1}$, pasture restoration provides the biggest opportunity for reducing emissions in the region.

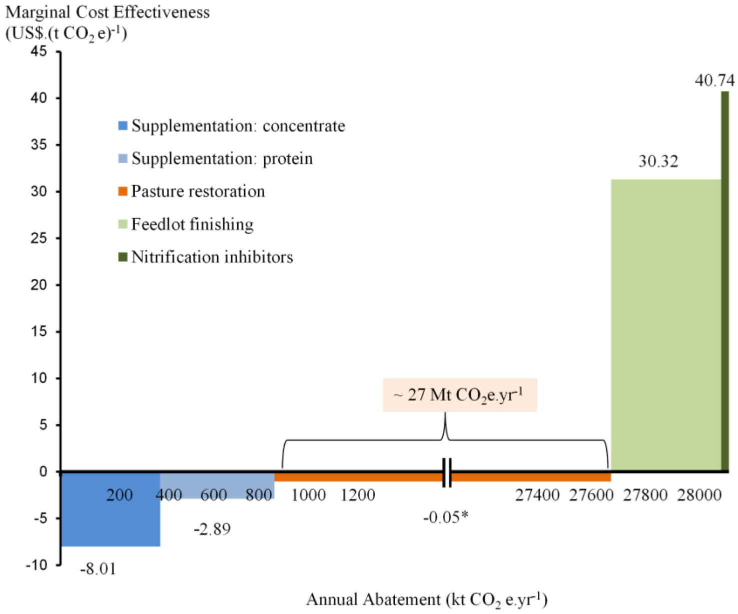

Figure 3: Marginal abatement cost schedule of key mitigation measures applicable to beef production in the *Cerrado*. The abatement potential (x-axis) and cost effectiveness (y-axis) of each measure was calculated as the average values obtained by adopting the measure over the 2006-2030 period.

The figures are averages values for the period of 2006-2030.

* Not in scale

The abatement potential (AP) for pasture restoration is 26.9 Mt $CO_2e.yr^{-1}$, comprising of two components: C sequestration and avoided deforestation, the latter accounting for 96% of this AP. Despite improved pasture productivity, less area is used to meet the same demand relative to the baseline, what means forage availability optimally matches that required for demand. In a scenario of increased forage productivity and higher beef demand, methane emissions would rise as result of increased animal numbers. Pasture restoration would improve the *Cerrado* average productivity from 10 to 11.2 t $DM.ha^{-1}.yr^{-1}$, an increase of 12% relative to the baseline. This increase would lead to an average C sequestration rate of 0.32 t $CO_2e.ha^{-1}.yr^{-1}$. This is a low C uptake potential when compared to values found by Maia et al. (2009), which showed that C sequestration rates of 2.24 t $CO_2e.ha^{-1}.yr^{-1}$ can be achieved in well-managed pastures in *Cerrado*. The carbon sequestration rate however, reflect the 2006-2030 period, after which, and in the long term, as pastures are intensified it will eventually reach equilibrium and therefore no more carbon is likely to be sequestered.

The AP of feedlot finishing is 470 kt $CO_2e.yr^{-1}$, but the measure cost-effectiveness US$ 13.32 t CO_2e^{-1} is high relative to supplementation.

Nitrification inhibitors are the least cost-effective measure considered. But this analysis only considered the application to N used for pasture and crops fertilization and excluded the application to animal excreta.

The results indicate that restoring degraded lands is the biggest opportunity for reducing emissions in the *Cerrado*. The AP of this measure is about 20 times greater than all the other measures combined.

An important assumption underpinning the MACC relates to the assumed measure adoption rates. With exception of feedlot finishing, the adoption rates are optimized, meaning the rates that maximizes the gross margin in the model.

Table 5: Mitigation measures adoption rate.

Mitigation Measure	Adoption rate	Unit
Supplementation: concentrate	12	%[1]
Supplementation: protein	2.2	%
Pasture restoration	314.7	10^3 $ha.yr^{-1}$
Feedlot finishing	15	%
Nitrification inhibitors	12.78	$g.ha^{-1}.yr^{-1}$

[1] Adoption rates for feedlot, protein and concentrate supplementation are calculated as the percentage of the total finished animals. The adoption rate of pasture restoration is the annual average area of restored pasture.

5. Discussion

To meet increasing domestic and export demand, the government of Brazil recognizes the need to foster sustainable agricultural intensification, which implies increased resource productivity while minimizing significant domestic and global external costs implicit in GHG emissions and deforestation. The results presented here suggest that a significant contribution to this objective can be made by targeting specific measures to improve yield. Specifically, pasture restoration, supplements and feedlot measures could reduce sector emissions by 24.1% by 2030. Moreover, by adopting only negative-cost measures (Fig. 3), it is possible to abate about 23.7% of baseline livestock emissions in the *Cerrado*, up to 2030. According to our results the restoration of degraded pastures offers the greatest abatement potential, involving the restoration of an average of 314.7 10^3 $ha.yr^{-1}$ in *Cerrado* grasslands.

Currently, it has been estimated that 50 % to 80 % of pastures in the Amazon and *Cerrado* are degraded (Macedo et al., 2014; Peron & Evangelista, 2004). Achieving a higher rate is likely to entail some initial investment costs to promote modified production practices and this is the purpose of the government's ABC program. ABC is an ambitious plan created to stimulate farmers and ranchers to adopt mitigation measures including restoration of degraded pastures, helping the country to meet the reduction targets presented at COP 15. ABC is the biggest sustainable agriculture fund running in Brazil, with a key objective of disbursing subsidized credit to the agricultural sector. The plan currently targets the recovery of 15 Mha in 10 years, which will lead to reductions up to 104 Mt

CO_2e, roughly 64% of the program total mitigation potential. But it does not include other relevant measures such as feed supplementation measures, which would normally be considered as privately profitable anyway.

The outcome of the ABC plan remains to be evaluated, but initial indications suggest that uptake of credit has been slower than anticipated (Claudio, 2012). Recent evidence from the Amazon Environmental Research Institute suggests that several institutional barriers have retarded the program, including a lack of publicity and information about the aims and the benefits of the program, difficulties in complying with program requirements, a lack of technical assistance, and producer scepticism about the private economic benefits of measures that are predominantly designed to address global external costs (Stabile et al., 2012).

Producers also perceive transaction costs in program compliance and a lack of basic infrastructure (Rada, 2013) that is needed to support increased productivity. In short, the ABC plan is confronting similar behavioural barriers in relation to non-adoption, identified in other mitigation studies, e.g. Moran et al. (2013), which need to be addressed before wider measure adoption can be expected.

6. Conclusion

This paper highlights how resource efficiency measures can be enacted (notionally within farm gate) in the *Cerrado* biome to help reconcile competing objectives of private yield improvements and the reduction of external costs. The analysis responds to the need to demonstrate the possibilities for sustainable intensification, allowing Brazil to meet economic growth ambitions for the sector.

The key finding from the use of the economic optimization model is the representation of the cost-effectiveness of key mitigation measures. Specifically, that pasture restoration is the most promising mitigation measure in terms of abatement potential volume and that it offers a cost saving for the livestock sector. By adopting these measures - pasture restoration, concentrate and protein supplementations - the *Cerrado* could reduce 23.7% of its emissions by 2030, while the total abatement potential of adopting all measures is 24.1%.

The analysis presented here has a number of caveats that potentially warrant further research. These include a more detailed representation of the biophysical heterogeneity of the *Cerrado* biome, more detailed treatment of the deforestation (and hence land sparing) processes and relaxation of the assumed equilibrium supply and demand conditions in the optimization model.

Nevertheless by highlighting cost-effective policy options, this paper contributes to our understanding of sustainable intensification processes as relevant to Brazilian livestock production.

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Appendix. Supplementary material

Appendix S1: Mathematical description

Appendix S2: Calculation of restoration costs and model calibration

Appendix S3: Supplementary tables S1-S8

Mathematical description

List of indexes

Symbol	Description	Range/value
i,j	Land use	{A, B, C, D, E, F, Corn(silage), Corn(grain), Soybeans}
p,q	Pasture level	{A, B, C, D, E, F}
c	Crops	{Corn(silage), Corn(grain), Soybeans}
kc	Cow breeding stage	{1, 2, ... , 12}
kh	Heifer age cohort	{1, 2, ... , 9}
ks	Steer age cohort	{1, 2, ... , 9}
kp	Age cohort of protein supplemented steers	{1, 2, ... , 6}
m	Production month	{1,2,...,M}
$CM_{(m)}$	Calendar month equivalent to production month *m*	{Jan, Feb, ... , Dec}
t	Year	{1, 2, ... , T}
$t_{(m)}$	Corresponding year to the production month *m*	{1, 2, ... , T}

List of decision variables

Symbol	Description	Unit

$CASH_m$	Cash in month *m*	M R$
CIN_m	Cash incomes in month *m*	M R$
$CNIH_m$	Costs of nitrification inhibitors in month *m*	M R$
COT_m	Cash outcomes in month *m*	M R$
CSC_m	Concentrate supplementation costs in month m	M R$
CSP_m	Protein supplementation costs in month m	M R$
EDA_t	Endogenous deforestation in year *t*	M ha
FSC_m	Number of finished steers under concentrate supplementation at month *m*	M head
FSF_m	Number of steers finished under feedlot system in month *m*	M head
IC_m	Number of cows inserted in the system in month *m*	M head
$IH_{m,kh}$	Number of heifers of age cohort *kh* inserted in the system in month *m*	M head
ISC_m	Incomes from concentrate supplementation in month *m*	M R$
$IS_{m,ks}$	Number of steers of age cohort *ks* inserted in the system in month *m*	M head
ISP_m	Income from protein supplementation in month *m*	M R$
$LUC_{t,i,j}$	Land use change (or pasture restoration) from *i* to *j* in year *t*	M ha
$LU_{t,j}$	Land use *j* in year *t*	M ha
NBC_m	Number of new born calves in month *m*	M head
PC_m	Number of purchased cows in month *m*	M head
$PFFP_m$	Pasture forage intake by protein supplemented steers in month *m*	M t.(M head)$^{-1}$
$PFSC_m$	Pasture forage intake by concentrate supplemented steers in month *m*	M t.(M head)$^{-1}$
$PH_{m,kh}$	Number of purchased heifers of age cohort *kh* in month *m*	M head
PSC_t	Quantity of beef produced from concentrate supplemented steers in year *t*	M t
$PS_{m,ks}$	Number of purchased steers of age cohort *ks* in month *m*	M head
PSP_t	Amount of beef produced from protein supplemented steers in year *t*	M t
$RFSC_{m,c}$	Amount of crop *c* required for concentrate supplemented steers in month *m*	M t
$RFSP_{m,c}$	Amount of crop *c* required for protein supplemented steers in month *m*	M t
$RPA_{t,p}$	Removed area from pasture *p* in year *t*	M ha

SC_m	Number of steers supplemented with concentrate in month *m*	M head
$SCP_{m,c}$	Stored amount of crop *c* in month *m*	M t
SCV_m	Number of stocked calves in month *m*	M head
$SCW_{m,kc}$	Number of stocked cows in breeding stage *kc* in month *m*	M head
SF_m	Number of stocked steers under feedlot system in month *m*	M head
SHB_m	Number of selected heifers for breeding in month *m*	M head
$SH_{m,kh}$	Number of stocked heifers of age cohort *kh* in month *m*	M head
$SP_{m,kp}$	Number of steers of category *kp* supplemented with protein in month *m*	M head
SSC_m	Number of steers selected for concentrate supplementation in month *m*	M head
$SSF_{m,k}$	Number of steers selected to feedlot in month *m*	M head
$SS_{m,ks}$	Number of stocked steers of age cohort *ks* in month *m*	M head
SSP_m	Number of steers selected for protein supplementation in month *m*	
TDM_m	Amount of dry minter transferred from month *m* to month *m+1*	M t
UC	Used money from own capital	M R$
WC_m	Number of weaned calves in month *m*	M head

List of parameters

Symbol	**Description**	**Unit**
	General coefficients	
$A_{o,j}$	Initial area of land use *j*	M ha
BD_t	Beef demand in year t	M t
c_{ins}	Cost of insemination	$R\$.head^{-1}$
c_{salt}	Cost of mineral salt	$R\$.t^{-1}$
DA_t	Exogenous deforestation	M ha

dmi_{CV}	Dry-matter intake of calves	$Kg.head^{-1}.mth^{-1}$
dmi_{kc}	Dry-matter intake of cows of breeding stage *kc*	$Kg.head^{-1}.mth^{-1}$
dmi_{kh}	Dry-matter intake of heifers of age cohort *kh*	$Kg.head^{-1}.mth^{-1}$
dmi_{ks}	Dry-matter intake of steers of age cohort *ks*	$Kg.head^{-1}.mth^{-1}$
DM_o	Initial pasture productivity	$t.ha^{-1}$
fc	Fixed costs per pasture area	$R\$.ha^{-1}.mth^{-1}$
ir	Savings interest rate	$\%.yr^{-1}$
mc_{CV}	Maintenance cost of calves	$R\$.head^{-1}.mth^{-1}$
mch_{kh}	Maintenance cost of heifers of age cohort *kh*	$R\$.head^{-1}.mth^{-1}$
mc_{kc}	Maintenance cost of cows of breeding stage *kc*	$R\$.head^{-1}.mth^{-1}$
mcs_{ks}	Maintenance cost of steers of age cohort *ks*	$R\$.head^{-1}.mth^{-1}$
oc_{Max}	Available own capital	M R$
prc_{kc}	Price of cows in breeding stage *kc*	$R\$.head^{-1}.mth^{-1}$
prh_{kh}	Price of heifer of age cohort *kh*	$R\$.head^{-1}.mth^{-1}$
$prod_{p,CM}$	Dry-minter productivity of pasture *p* in the calendar month *CM*	$t.ha^{-1}.mth^{-1}$
prs_{ks}	Price of steers of age cohort *ks*	$R\$.head^{-1}.mth^{-1}$
tc	Cattle trading cost	$R\$.head^{-1}$
α	Adjustment parameter for the end of production	dimensionless
γ_{CC}	Cull cow carcass yield	dimensionless
γ_H	Heifer carcass yield	dimensionless
γ_S	Steer carcass yield	dimensionless
ζ	Ratio of herbage mass loss due to grazing (grazing efficiency)	dimensionless
μ_{CV}	Calf mortality rate	dimensionless
μ_{CW}	Cow mortality rate	dimensionless
μ_{kh}	Mortality rate of heifers of age cohort *kh*	dimensionless
μ_{ks}	Mortality rate of steers of age cohort *ks*	dimensionless
$\sigma_{CM(m)}$	Ratio of herbage mass loss due senescence	dimensionless

$\tau_{CM(m)}$	Minimum herbage mass (dry minter) transference in month CM(m)	$t.ha^{-1}.mth^{-1}$
ψ	Fraction of feedlot steers in relation to the total slaughtered animals	dimensionless
ω_{CC}	Weight of cull cows	kg
ω_S	Weight of steers finished under pasture	kg
ω_H	Weight of heifers finished under pasture	kg
Pasture restoration coefficients		
INAi,j	Amount applied of input (or service) *inp* on land use (or pasture restoration) from land use *i* to *j*	$kg.ha^{-1}$
$c_{i,j}$	Cost of land use change (or pasture restoration)	$R\$.ha^{-1}$
$NA_{i,j}$	Nitrogen application on land use change (or pasture restoration) from land use *i* to *j*	$kg.ha^{-1}$
Feedlot finishing coefficients		
dmi_{FL}	Dry-matter intake of feedlot steers	$Kg.head^{-1}.mth^{-1}$
nfc_{FL}	Non feed costs of feedlot finishing	$R\$.head^{-1}.mth^{-1}$
pr_{FL}	Selling price of feedlot steers	$R\$.head^{-1}.mth^{-1}$
$prr_{c,FL}$	Fraction of crop *c* in the feedlot ration composition	dimensionless
$prr_{salt,FL}$	Proportion of mineral salt in feedlot ration	%
γ_{FL}	Feedlot steer carcass yield	dimensionless
μ_{FL}	Mortality rate of feedlot steers	dimensionless
ω_{FL}	Weight of steers finished under feedlot	kg
Supplementation concentrate coefficients		
c_{urea}	Cost of mineral urea	$R\$.kg^{-1}$
dmi_{SC}	Steers' dry-matter intake of concentrate supplementation	$kg.head^{-1}.mth^{-1}$
mc_{SC}	Maintenance cost of supplemented concentrate steers	$R\$.head^{-1}.mth^{-1}$
nfc_{SC}	Non feed costs of supplementation concentrate	$R\$.head^{-1}.mth^{-1}$
$pdmi_{SC}$	Forage dry matter intake of concentrate supplemented steers	$R\$.kg^{-1}.mth^{-1}$
$prr_{c,SC}$	Proportion of crop *c* in the concentrate supplement	dimensionless

$prr_{salt,SC}$	Proportion of mineral salt in concentrate supplement	dimensionless
$prr_{Urea,SC}$	Proportion of urea in concentrate supplement	dimensionless
pr_{SC}	Selling price of steers finished under supplementation concentrate	$R\$.head^{-1}$
γ_{SC}	Carcass yield of concentrate supplemented steers	dimensionless
μ_{SC}	Mortality rate of supplemented concentrate steers	dimensionless
ω_{CS}	Finishing weight of Concentrate supplement steer	kg
Supplementation protein coefficients		
$dmi_{SP,kp}$	Dry-matter intake of concentrate supplementation of steer of age cohort *kp*	$kg.head^{-1}.mth^{-1}$
msp_{kp}	Maintenance cost of supplemented protein steer of age cohort *kp*	$R\$.head^{-1}.mth^{-1}$
nfc_{SP}	Non feed costs of supplementation protein	$R\$.head^{-1}.mth^{-1}$
$pdmi_{kp}$	Forage dry matter intake of concentrate supplemented steers of age cohort kp	$kg.head^{-1}.mth^{-1}$
$prr_{c,SP}$	Proportion of crop *c* in the protein ration	dimensionless
$prr_{NaCl,SP}$	Proportion of NaCl in protein ration	dimensionless
$prr_{salt,SP}$	Proportion of mineral salt in protein ration	dimensionless
$prr_{urea,SP}$	Proportion of urea in protein ration	dimensionless
pr_{SP}	Price of steer of age cohort *kp* supplemented with protein	$R\$.head^{-1}$
γ_{SP}	Carcass yield of protein supplemented steers	dimensionless
μ_{kp}	Mortality rate of supplemented protein steers of age cohort *kp*	dimensionless
ω_{kp}	Weight of protein supplemented steer of age cohort *kp*	kg
Nitrification inhibitors coefficients		
c_{NIH}	Cost of nitrification inhibitors	$R\$.kg^{-1}$
$cv_{N,N2O}$	Conversion factor of N into N_2O	dimensionless
p_{NIH}	Nitrification inhibitors efficiency	dimensionless
a_{NIH}	Nitrification inhibitors application (proportional to N application)	dimensionless
RL	Proportion of N saved by using nitrification inhibitors	dimensionless
GHG emissions coefficients		

ce_m	Total cattle emissions (in the baseline)	Kg $CO_2e.mth^{-1}$
$ce_{m,SC}$	Total cattle emissions from concentrate supplemented steers	Kg $CO_2e.mth^{-1}$
$ce_{m,SC}$	Total cattle emissions from protein supplemented steers	Kg $CO_2e.mth^{-1}$
$cs_{t,j}$	Soil organic carbon stock under land use *j* in year *t*	Mt C
$cv_{N\rightarrow N2O}$	Conversion factor of N to N_2O	dimensionless
de_t	Total natural vegetation emissions	Mt $CO_2e.yr^{-1}$
ec_{kc}	Emission factor of cow of age cohort *kh*	Kg $CO_2e.head^{-1}.mth^{-1}$
e_{CV}	Emissions factor of calves	Kg $CO_2e.head^{-1}.mth^{-1}$
e_{FL}	Emissions factor of feedlot steers	Kg $CO_2e.head^{-1}.mth^{-1}$
eh_{kh}	Emission factor of heifer of age cohort *kh*	Kg $CO_2e.head^{-1}.mth^{-1}$
es_{ks}	Emission factor of steer of age cohort *ks*	Kg $CO_2e.head^{-1}.mth^{-1}$
fe_t	Total N-based fertilizers emissions (without nitrification inhibitors)	Mt $CO_2e.yr^{-1}$
$fe_{t,NIH}$	Total N-based fertilizers emissions (with nitrification inhibitors)	Mt $CO_2e.yr^{-1}$
r	Carbon respiratory losses parameter	dimensionless
$\Delta cs_{t,j}$	Amount of carbon sequestration under land use *j* in year *t*	Mt $C.yr^{-1}$
ε_j	Carbon equilibrium stock under land use *j*	$t.ha^{-1}$
θ	Natural vegetation above ground biomass	t $C.ha^{-1}$
σ	Natural vegetation below ground biomass	t $C.ha^{-1}$

$$\text{Max } CASH_M \quad (1)$$

S.t:

$$LU_{t,j} = A_{o,j} \quad \forall j \qquad (2)$$

$$LU_{t,p} = LU_{t-1,p-\partial(t)} + \sum_i (LUC_{t,i,p} - LUC_{t-1,p-\partial(t),i}) - RPA_{t,p}$$
$$t > 1, \mathrm{p} \neq \mathrm{C} \qquad (3)$$

$$LU_{t,p} = LU_{t-1,p-\partial(t)} + \sum_i (LUC_{t,i,p} - LUC_{t-1,p-\partial(t),i}) + DA_t + EDA_t - RPA_{t,p}$$
$$t > 1\,,\; p = \mathrm{C} \qquad (4)$$

$$LU_{t,c} = \sum_i LUC_{t,i,c}\,, \quad t > 1 \qquad (5)$$

$$\sum_j LUC_{t,p,j} + RPA_{t,p} \leq LU_{t-1,p}\,, \quad t > 1 \qquad (6)$$

$$\sum_j LUC_{t,c,j} \leq LU_{t-1,c}\,, \quad t > 1 \qquad (7)$$

$$SS_{m,ks} = IS_{m,ks} + (1-\mu_{ks})SS_{m-1,ks} + \sum_r \prod_{i=1}^{r} (1-\mu_{ks-i})^3 IS_{m-3\mathrm{r},ks-r} -$$
$$- \sum_r \prod_{i=1}^{r} (1-\mu_{ks+1-i})^3 IS_{m-3\mathrm{r},ks-r+1}\,, \forall m\,, ks < 9\,, \quad r \in \{1,2,\ldots\} \qquad (8)$$

$$SS_{m,ks} = \sum_{r}\prod_{i=1}^{r}(1-\mu_{ks-i})^{3} IS_{m-3r,k-r} \;, \forall m \;, ks = 9 \;, \quad r \in \{1,2,...\} \qquad (9)$$

$$IS_{m,ks} = 0.5WC_{m} + PS_{m,ks} \;, \quad \forall m, \quad ks = 1 \qquad (10)$$

$$IS_{m,ks} = PS_{m,ks} - SSF_{m} \;, \quad \forall m, \quad ks = 7 \qquad (11)$$

$$IS_{m,ks} = PS_{m,ks} \;, \quad \forall m, \quad ks > 1 \wedge ks \neq 7 \qquad (12)$$

$$SH_{m,kh} = IH_{m,kh} + (1-\mu_{kh})SH_{m-1,ks} + \sum_{r}\prod_{i=1}^{r}(1-\mu_{ks-i})^{3} IH_{m-3r,ks-r} - \\ - \sum_{r}\prod_{i=1}^{r}(1-\mu_{kh+1-i})^{3} IH_{m-3r,kh-r+1} \;, \quad \forall m, \quad kh < 9, \quad r \in \{1,2,...\} \qquad (13)$$

$$SH_{m,kh} = \sum_{r}\prod_{i=1}^{r}(1-\mu_{kh-i})^{3} IH_{m-3r,kh-r} \;, \forall m, \quad kh = 9, \quad j \in \{1,2,...\} \qquad (14)$$

$$IH_{m,kh} = 0.5WC_{m} + PH_{m,kh} \;, \quad \forall m, \quad kh = 1 \qquad (15)$$

$$IH_{m,kh} = PH_{m,kh} - SHB_{m} \;, \forall m, \quad kh = 7 \qquad (16)$$

$$IH_{m,kh} = PH_{m,kh} \;, \forall m, \quad kh > 1 \wedge kh \neq 7 \qquad (17)$$

$$SCW_{m,kc} = (1-\mu_{CW})SCW_{m-1,kc} + IC_{m} - IC_{m-9} \;, \forall m \;, kc = 1 \qquad (18)$$

$$SCW_{m,kc} = (1-\mu_{CW})^{15+18*3}\ IC_{m-(15+18*3)}\ ,\forall m\ ,kc = 12 \tag{19}$$

$$SCW_{m,kc} = (1-\mu_{CW})SCW_{m-1,kc} + (1-\mu_{CW})^{18ord(kc)} IC_{m-18ord(kc)} - (1-\mu_{CW})^{9+18ord(kc)} IC_{m-(9+18ord(kc))}\ ,\forall m, kc \in P = \{4,7,10\} \tag{20}$$

$$SCW_{m,kc} = (1-\mu_{CW})SCW_{m-1,kc} + (1-\mu_{CW})^{9+18(ord(kc)-1)} IC_{m-(9+18(ord(kc)-1))} - (1-\mu_{CW})^{15+18(ord(kc)-1)} IC_{m-(15+18(ord(kc)-1))}\ ,\forall m, kc \in L = \{2,5,8,11\} \tag{21}$$

$$SCW_{m,kc} = (1-\mu_{CW})SCW_{m-1,kc} + (1-\mu_{CW})^{15+18(ord(kc)-1)} IC_{m-(15+18(ord(kc)-1))} - (1-\mu_{CW})^{18+18(ord(kc)-1)} IC_{m-(18+18(ord(kc)-1))}\ ,\forall m, kc \in N = \{3,6,9\} \tag{22}$$

$$IC_m = PH_m + SHB_m\ ,\forall m \tag{23}$$

$$NBC_m = \sum_{i=0}^{3} IC_{m-(9+18i)}\ ,\forall m \tag{24}$$

$$SCV_m = (1-\mu_{CV})SCV_{m-1} + NBC_m - (1-\mu_{CV})^6 NBC_{m-6}\ ,\forall m \tag{25}$$

$$WC_m = (1-\mu_{CV})^6 NBC_{m-6}\ ,\forall m \tag{26}$$

$$FSF_m = (1-\mu_{FL})^2 SSF_{m-2}\ ,\forall m \tag{27}$$

$$SF_m = (1-\mu_{FL})SF_{m-1} + SSF_m - FSF_m\ ,\forall m \tag{28}$$

$$\sum_{m \mid \left\lceil \frac{m}{12} \right\rceil = t} FSF_m = \psi \left(\sum_{m \mid \left\lceil \frac{m}{12} \right\rceil = t} (SS_{m,9} + SH_{m,9} + FSF_m + SCW_{m,12}) \right), \forall t$$

(29)

$$(1+\xi)\Big(\sum_{ks} dmi_{ks} SS_{m,ks} + \sum_{kh} dmi_{kh} SH_{m,kh} + \sum_{kc} dmi_{kc} SCW_{m,kc} + dmi_{CV} SCV_m\Big) + TDM_m$$
$$= \sum_{p} prod_{p,CM(m)} LU_{t(m),p} + (1-\sigma_{CM(m)})TDM_{m-1} \leq 0 \quad , \quad 1 < m \leq M$$

(30)

$$\tau_{CM(m)} \sum_{p} LU_{t,p} - TDM_m \leq 0 \, , \quad \forall m$$

(31)

$$SCP_{m,c} = SCP_{m-1,c} + prod_{c,CM(m)} LU_{t(m),c} - prr_{c,FL} dmi_{FL} SF_m \quad , \forall c, \forall m$$

(32)

$$\sum_{m \mid \left\lceil \frac{m}{12} \right\rceil = t} (\gamma_{\mathrm{S}} \omega_{\mathrm{S}} SS_{m,\mathrm{ks}=9} + \gamma_{\mathrm{H}} \omega_{\mathrm{H}} SH_{m,kh=9} + \gamma_C \omega_C SCW_{m,kc=12} + \gamma_{FL} \omega_{FL} FSF_m) = BD_t \ , \forall t$$

(33)

$$CIN_m = prs_9 SS_{m,9} + \mathrm{prh}_9 SH_{m,9} + pr_{FL} FSF_m + prc_{12} SCW_{m,12} \, , \quad \forall m$$

(34)

$$
\begin{aligned}
COT_m = {} & fc\sum_{p} LU_{t,p} + \sum_{ks=1}^{8}(tc + prs_{ks})PS_{m,ks} + \sum_{kh=1}^{8}(tc + prh_{kh})PH_{m,kh} + (tc + prc_1)PC_m + \\
& + \sum_{ks} mcs_{ks}SS_{m,ks} + \sum_{kh} mch_{kh}SH_{m,kh} + \sum_{kc} mc_{kc}SCW_{m,ks} + mc_{CV}SCV_m + \\
& + (nfc_{FL} + c_{salt}\, prr_{salt,FL}\, dmi_{FL})(SF_m + FSF_m) + c_{ins}SHB_m + LI_m \sum_{i}\sum_{j} c_{i,j} LUC_{t(m),i,j} \quad ,\forall m
\end{aligned}
$$

(35)

$$CASH_m = UC + CIN_m - COT_m \;\;, \; m = 1$$ (36)

$$UC \le oc_{max}$$ (37)

$$CASH_m = CASH_{m-1} + CIN_m - COT_m \;\;, m > 1$$ (38)

$$
\begin{aligned}
CASH_m = {} & CASH_{m-1} + CIN_m - COT_m - (1 + ir)^T\, UC + \\
& + \alpha\left(\sum_{ks=1}^{8} prs_{ks}SS_{m,ks} + \sum_{kh=1}^{8} prh_{kh}SH_{m,kh} + prc_{kc}\sum_{kc} SCW_{m,kc} \right) \\
& m = M
\end{aligned}
$$

(39)

$$FSC_m = (1 - \mu_{SC})^2\, SSC_{m-2} \;\;, \; \forall m$$ (40)

$$SC_m = (1 - \mu_{SC})SC_{m-1} + SSC_m - FSC_m \;\;, \; \forall m$$ (41)

$$PSC_t = \sum_{m \,\mid\, \left\lceil \frac{m}{12} \right\rceil = t} \gamma_{SC}\,\omega_{SC}\,FSC_m \;\;, \; \forall t$$

(42)

$$CSC_m = ((c_{urea}\, prr_{urea,SC} + c_{salt}\, prr_{salt,SC})dmi_{SC} + nfc_{SC} + mc_{SC})SC_m \quad , \forall m \tag{43}$$

$$ISC_m = pr_{SC} FSC_m \quad , \forall m \tag{44}$$

$$PFSC_m = (1+\xi)\, pdmi_{SC} SC_m \ , \forall m \tag{45}$$

$$RFSC_{m,c} = prr_{c,SC} dmi_{SC} SC_m , \ \forall c , \forall m \tag{46}$$

$$SP_{m,kp} = (1-\mu_{kp})SP_{m-1,kp} + SSP_m - (1-\mu_{kp})^3 SSP_{m-3,kp} , \ kp = 1 , \forall m \tag{47}$$

$$SP_{m,kp} = (1-\mu_{kp})SP_{m-1,kp} + \prod_{r=1}^{kp-1}(1-\mu_r)^3 SSP_{m-3(kp-1)} - \prod_{r=1}^{kp}(1-\mu_r)^3 SSP_{m-3kp} , \ kp > 1, \forall m \tag{48}$$

$$PSP_t = \sum_{m \mid \left\lceil \frac{m}{12} \right\rceil = t} \gamma_{SP} \omega_{kp} SP_{m,kp} \quad , kp = 6 \ , \forall t \tag{49}$$

$$CSP_m = (c_{urea}\, prr_{urea,SP} + c_{salt}\, prr_{salt,SP} + c_{NaCl}\, prr_{NaCl,SP}) \sum_{kp} dmi_{SP,kp} SP_{m,kp} + \\ + \sum_{kp} (nfc_{SP} + msp_{kp}) SP_{m,kp} \ , \forall m \tag{50}$$

$$ISP_m = pr_{kp} SP_{m,kp} \quad , kp = 6 \, , \, \forall m \qquad (51)$$

$$PFSP_m = (1+\xi)\sum_{kp} pdmi_{kp} SP_{m,kp} \quad , \forall m \qquad (52)$$

$$RFSP_{m,c} = prr_{c,SP} \sum_{kp} dmi_{SP,kp} SP_{m,kp} \, , \, \forall c \, , \forall m \qquad (53)$$

$$CNIH_m = c_{NIH} \, a_{NIH} \, (1-RL) \sum_i \sum_j NA_{i,j} \, LUC_{t(m),i,j} \, LI_m \qquad (54)$$

Objective function

Eq. 1 corresponds to the maximization of cash/income at the last month of production (month *M*), i.e., gross margin. $CASH_M$ (M R$) represents cash at the very last month (*M*) of production. **Eq. 1** is equivalent to the expanded equivalent **Eq. 39** .

Land use dynamics

Eq. 2 is responsible for allocating the initial land use of pastures types {*A*,*B*,*C*,*D*,*E*,*F*} and crops {*Corn(silage)*,*Corn(grain)*,*Soybeans*}. $LU_{t,j}$ (M ha) accounts for the allocated area of land use/pasture types *j* in year *t*, *Ao*,*j* represents the initial allocation of each land use/pasture types.

Eq. 3 represents the pasture allocation, allowing for degradation, pasture restoration and land use change decisions. As degradation was assumed to occur biannually, the binary parameter vector $\delta(t)$ is used as an index as follows:

$$\delta(t) = \begin{cases} 1, \text{ if } t \text{ is an odd number} \\ 0, \text{ if } t \text{ is even} \end{cases}$$

The area of pasture p in year t ($LU_{t,p}$) is given by the area of pasture p in the previous year $t-1$ ($LU_{t-1,p}$) or the area pasture p-1 ($LU_{t-1,p-1}$) if t is a year where degradation occurs, i.e., t is an odd number, plus the area from other land uses/pasture types i to pasture p in year t ($\sum_i LUC_{t,i,p}$), less the area converted from pasture p to the other land uses/pasture types i ($\sum_i LUC_{t,p,i}$), subtracted from the area of pasture p removed in year t ($RPA_{t,p}$).

Eq. 4 is identical to **Eq. 3** except for land expansion (endogenous and exogenous), which is allocated to pasture $p=C$ (due to equivalence of natural vegetation productivity with pasture level C. DA_t represents the exogenous pasture expansion and EDA_t the exogenous expansion term, i.e., extra deforestation required to meet demand in year t.

Eq. 5 expresses the crop allocation, which is a simpler dynamic than pasture: every year crops need to be planted and harvested. **Eq. 5** says the area of crop c in year t is equivalent to the sum of converted (or re-planted in the case of i=c) area from all possible land uses to crop c ($\sum_i LUC_{t,i,c}$).

Eq. 6 and **Eq. 7** are used to constrain the land use change variables according to the available area, respectively for pastures and crops. **Eq. 6** says the area converted from pasture *p* to improved pastures (restoration) or to crops in year *t*, (first term in the right-hand side (RHS)), has to be no greater than the available area in the previous year *t*-1, i.e., $LU_{t-1,p} - RPA_{t,p}$. **Eq. 7** is similar to **Eq. 6** but for crops (unlike pasture, it is assumed no crop area is removed).

Grazing steer dynamics

Eq. 8 models the steer fattening until slaughter weight – represented as the transfer from age cohorts *ks-1*, *ks-2, ks-3*,… to *ks*. The number of steers (M heads) in the system in time step (month) *m* ($SS_{m,ks}$) is given by the combination of 4 terms: (i) the number of steers that were inserted in the system in that month ($IS_{m,ks}$); (ii) the number of steers *ks* in the previous month less the mortality rate (second term in the RHS); (iii) the number of steers that are changing from the previous age cohorts to *ks* (third term in the RHS), and (iv) the number of steers that are changing from *ks* to the next cohort *ks+1* (fourth term in the RHS). (i) and (ii) are straightforward; (iii) is given by the number of steers that were inserted in the system as age cohort *ks-1* three months before month *m*, plus the number inserted 6 months before as category *ks-2* and so forth (every 3 months steers change to the next age cohort), i.e., $IS_{m-3,ks-1} + IS_{m-6,ks-2} + IS_{m-9,ks-3} + IS_{m-12,ks-4} + \ldots =$ $\sum_{r} IS_{m-3r,ks-r}$, the term multiplying $IS_{m-3r,ks-r}$ ($\prod_{i=1}^{r}(1-\mu_{ks-i})^{3}$) accounts for accumulated transfer rate according to mortality rate for each element in the sum (cubed because the mortality rate is a monthly value); (iv) is analogous to (iii).

Eq. 9 accounts for the number of finished steers, i.e., age cohort 9. In that cohort there is no monthly transfer from the same cohort, i.e, once a steer reach age cohort 9, it is slaughtered.

Eq. 10 accounts for the number of steers of the first age cohort inserted into the system (calves) in month m ($IS_{m,ks=1}$). An animal can be inserted into the grazing system by: (i) breeding: i.e., a calf is born in the system (first term in the RHS) or (ii) by being purchased (second variable on the RHS). Let WC_m be the number of newborn calves in month m and $PS_{m,ks}$ the number of calves purchased in that month. It is assumed half of the animals born are males and half females; thus WC_m is multiplied by 0.5.

Eq. 11 says the number of inserted steers of age cohort ks=7 is given by the number of purchased steers ($PS_{m,ks=7}$) less the number of steers allocated into feedlot systems (SSF_m).

Eq. 12 says that the number of inserted steers of age cohort $ks \neq 7$ equals the number of purchased steers.

Grazing heifer dynamics

Heifers are finished under the grazing system as occurs with steers, or selected to become cows, and thus generate calves in the system.

Let $SH_{m,kh}$ represents the number of heifer of age cohort *kh* in month *m*; $IH_{m,kh}$ the number of heifers *kh* inserted in the system in month *m*; $PH_{m,kh}$, the number of heifers purchased in month *m* and SHB_m the number of heifers selected for breeding in that month. Then **Eq. 13** - **17** are respectively analogous to Eq. **8** - **12**, but for heifers. Heifers cannot be moved to feedlot systems in the same way as steers, instead heifers of age cohort *kh*=7 can be selected for breeding process (variable SHB_m in **Eq. 16**) and then added to the cow-calf equation dynamics (**Eq. 23**).

Breeding dynamics

Each cow generates one calf per cycle, a cycle is composed of three breeding stages: (i) pregnant stage, (ii) lactation stage, and (ii) non-lactation stage. After four cycles, cows are removed from breeding process and slaughtered (cull cows). The cycles correspond to cow transfer from breeding stage *kc=1* up to *kc=12*:

Extended Table 9: Breeding stages

Breeding stage (*kc*)	Description	Duration (months)
1	1st pregnancy	9
2	1st lactation	6
3	1st non-lactation	3
4	2nd pregnancy	9
5	2nd lactation	6
6	2nd non-lactation	3
7	3rd pregnancy	9

8	3rd lactation	6
9	3rd non-lactation	3
10	4th pregnancy	9
11	4th lactation	6
12	4th non-lactation (cull cow)	1

As for the steer and heifer dynamics, the number of cows in the system (stocked cows) is given by the transfer of previous categories (or age cohorts).

Eq. 18 - **22** represent the transfer across the breeding stages, starting from 1st pregnancy ($kc=1$) until the last stage ($kc=12$) when cows are removed from the breeding system.

Eq. 18 says that the number of cows in the initial breeding stage (kc=1) in month m ($SCW_{m,ks}$) is given by the number of cows in stage kc in m-1, less the mortality rate μ_{CW} (first term in the RHS), plus the cows that are inserted into the breeding system in that month (IC_m), less the cows leaving stage $kc=1$, i.e., cows that entered the system 9 months before m (IC_{m-9}).

Eq. 19 says the number of cows in the last breeding stage ($SCW_{m,kc=12}$) is given by the number of cows inserted in the system 4 cycles before, i.e, $IC_{m-(15+18*3)}$. The first 3 cycles are comprised of 9 months of pregnancy, 6 months of lactation and 3 months resting, totaling 18 months, the last cycle does not include the resting stage, i.e., pregnancy +lactation, totaling 15 months.

Eq. 20 represents the dynamics of cows in the pregnancy breeding stages (for $kc>1$), i.e for $kc \in P = \{4,7,10\}$, where P is the set of indexes of cows in the pregnancy breeding stage. Here, the number of cows in month m ($SCW_{m,kc}$) is given by the number in the previous month less the mortality rate (first term in the RHS), plus the cows inserted in the system one cycle before for kc=4, two cycles before for kc=7 and 3 cycles before for kc=10, i.e., cows inserted in ord(kc)*18 months before month m ($IC_{m-18ord(kc)}$). The term $(1-\mu_{CW})^{18ord(kc)}$ is the accumulated mortality rate. Similarly, the number of cows moving from the pregnancy stages to the lactation stages in month m is equivalent the number of cows that were inserted as in the second term in the RHS, but 9 months before m , i.e., $IC_{m-(9+18ord(kc))}$.

Eq. 21 and **22** follow the same logic of **Eq. 20** but represent the number of cows in lactation ($kc \in L = \{2,5,8,11\}$), and the number cows in non-lactation (or resting stage) ($kc \in N = \{3,9,6\}$), respectively.

Eq. 23 indicates the number of cows inserted into the breeding process in month m (IC_m) j given by the number of purchased (PH_m) plus the number of selected heifers (SHB_m).

Eq. 24 accounts for the number of newborn calves in month m. Let NBC_m be the number of births in month m, then NBC_m is equivalent to the number of cows inserted into the breeding system at m-9, (one cow generates one calf) plus the number of cows inserted m-18 (duration of a cycle), and so forth, until it completes 4 cycles, i.e., $\sum_{i=0}^{3} IC_{m-(9+18i)}$.

Eq. 25 accounts for the number of calves in the system. Let SCV_m be the number of calves in month m, it is then given by the transfer from m-1 (first term in the RHS), plus births in m (NBC_m), less the births at m-6 (NBC_{m-6}), since calves are fed by cows for 6 months, with all terms multiplied by respective monthly transfer with accumulated mortality rate, where μ_{CV} represents the monthly mortality rate for calves.

Eq. 26 gives the number of weaned calves (WC_m) in month m, i.e., calves born in m-6, multiplied by accumulated transfer with mortality rate, $(1-\mu_{CV})^6 NBC_{m-6}$. The weaned calves are then allocated half to steers $ks=1$ and half to heifers $kh=1$, respectively to **Eq. 10** and **Eq. 15**.

Feedlot finishing

Eq. 27 accounts for the number of finished steers under the feedlot system in month m (FSF_m). Once a steer is selected for the feedlot (from ks=7), it takes two months to slaughter. FSF_m is equivalent to the number of steers removed from grazing system (SSF_m), multiplied by the two-months accumulated age cohorts transfer rate $(1-\mu_{FL})^2$, where μ_{FL} is the monthly mortality rate of feedlot steers.

Eq. 28 accounts for the number of steers in the feedlot (SF_m) - before slaughter. SF_m is given by the transfer from the previous month $(1-\mu_{FL})SF_{m-1}$, plus steers inserted into the feedlot in that month (SSF_m), less the slaughtered steers in that month (FSF_m).

Eq. 29 establishes the proportion of feedlot animals, i.e. the number of feedlot steers in year t has to be a proportion ψ of the total annual slaughtered cattle among grazing steers, feedlot steers, grazing heifers and discarded cows. $SS_{m,9}$ and $SH_{m,9}$ are the numbers of slaughtered animals (last age cohort) respectively for steers and heifers, $SCW_{m,12}$, the number of cull cows in month *m*. The sum over *m* such that $\left\lceil \frac{m}{12} \right\rceil = t$ (ceiling of *m* = t) is used make the sum over the months of the equivalent year, i.e., if t=1 then m ϵ {1,2,…12}, if t=2 then m ϵ {13,14,…,24} and so forth.

Forage budgeting

Eq. 30 represents the feed budgeting of all grazing cattle, i.e., the balance of demanded dry matter (terms in the left hand side (LHS)) and forage availability (terms in the RHS). Let dmi_{ks}, dmi_{kh}, dmi_{kc} and dmi_{CV} be the dry matter intake (in $kg.hd^{-1}.mth^{-1}$) of respectively steers of age cohort *ks*, heifer of age cohort *kh*, cows in breeding stage *kc*, and calves. The total demanded dry matter is given by the total consumed (the sums over the cohorts indexes). Because there is loss of dry matter due to animal grazing, a dimensionless parameter (ζ) is used to represent the dry matter losses proportional to the total dry matter consumed, therefore total consumption is multiplied by ($1+ \zeta$). The model does not require that all available dry matter has to be consumed in a given month, i.e., part of it can be transferred to the next month by a variable representing the dry matter not consumed in month *m*, TDM_m (slack variable). In the RHS of the inequality the available dry matter in month *m* is represented. *Let* $prod_{p,CM(m)}$ be the dry matter productivity ($t.ha^{-1}.mth^{-1}$) of pasture type *p* in the calendar month *CM(m)*, thus the first term in the RHS represents the total dry matter produced in month *m*. The available dry matter not consumed in month *m*-1 is transferred to month *m*, less dry matter losses due to senescence process for the equivalent calendar month ($\sigma_{CM(m)}$).

Eq. 31 The slack variable TDM_m in **Eq. 30** has to be greater than a minimum value, i.e., not all the available dry matter (organic matter above ground) can be consumed by grazing cattle. Instead, there is a lower bound for TDM_m, i.e., a minimum of dry-matter per hectare that has to be transferred from one month to another, represented by $\tau_{CM(m)}$.

Eq. 32 represents stocking of crops produced on the farm. Let $SCP_{m,c}$ be the amount of crop stocked in month m (M t), it is given by the stock from the previous month ($SCP_{m-1,c}$), plus the amount of crop c produced in month m (second term in the RHS), where $prodc,_{CM(m)}$ is the productivity of crop c in the calendar month $CM(m)$ (in t.ha^{-1}), less the amount of crop c that is consumed for ration formulation for feedlot cattle (third term in the RHS), where dmi_{FL} is the ration dry matter intake (t.hd^{-1}.mth^{-1}) of feedlot steers and $prr_{c,FL}$ is a dimensionless parameter representing the proportion of the intake that is obtained from crop c, i.e., proportion of crop c in the ration formulation.

Beef demand

Eq. 33 is the demand constraint. Let γ_S, γ_H, γ_C and γ_{FL} represent the carcass yield of grazing finished steers, heifers, cull cows and feedlot finished steers, respectively; and ω_S, ω_H, ω_C and ω_{FL} the finishing weight of grazing steers, heifers, cull cows and feedlot finished steers (kg.hd^{-1}), respectively. Total produced meat is equivalent to the product of carcass yield by finished weight and number of finished animals in month m of each category (then summed over the equivalent months of each year using the celling operator ($\lceil \; \rceil$), as in **Eq.29**).

Cash flow

Eq. 34 represents farm incomes from the sale of finished animals. Let CIN_m be the farm incomes in month m, prs_9, prh_9, pr_{FL} and prc_{12} be the selling prices of finished grazing steers, heifers, finished feedlot steers and cull cows (R$.hd^{-1}), respectively. Income is the product of cattle selling prices times the number of finished cattle, i.e., finished steers in month m ($SS_{m,9}$), heifers ($SH_{m,9}$), feedlot steers (FSF_m) and culled cows ($SCW_{m,12}$).

Eq. 35 represents the costs of the farm in month m (COT_m), composed of: (i) fixed costs per pasture area (first term in the RHS), where fc is the cost per hectare, multiplied by the total area in year t ($\sum_p LU_{t,p}$); (ii) cost of purchasing animals, i.e, price and transactions costs (second to fourth term in the RHS), where prs_{ks}, prh_{kh} and $prc_{kc=1}$ are the purchasing price of steers of age cohort ks, heifers of age cohort kh and cows in breeding stage kc=1, (R$.hd^{-1})respectively; tc is a parameter representing the transaction cost per head. The summations ranges from 1 to 8 because ks=9 or kh=9 correspond to finished cattle; (iii) grazing cattle maintenance costs (from fifth to eighth term in the RHS), where mcs_{ks}, mch_{kh}, mc_{kc} and mc_{CV} are the maintenance costs per head for steers, heifers, cows and calves, respectively; (iv) feedlot non-feed costs (ninth term in the RHS), where nfc_{FL} is the maintenance cost for feedlot animals (R$.hd^{-1}); c_{salt} is the cost of mineral salt used in ration formulation; $prr_{salt,FL}$ is a dimensionless parameter that represents the proportion of salt in the feedlot ration composition; (v) cost of inseminating heifers (tenth term in the RHS), where c_{ins} is the insemination cost per head; (vi) land use change and pasture restoration costs (last term in the RHS), where $c_{i,j}$ is the cost to restore one hectare of pasture *i* to improved pasture *j* (or the cost of changing one hectare from land use *i* to *j*). The land use change/restoration cost is always discounted in the first month for every year by using a binary parameter LI_m, where $LI_m = 1$ if m=*January*, otherwise $m=0$.

Eq. 36 says the cash ($CASH_{m=1}$) in the first production month consists of own used capital (*UC*) plus incomes, less costs.

Eq. 37 sets a constraint on used own capital availability, where oc_{max} is the available own capital.

Eq. 38 says the subsequent monthly cash ($CASH_m$) (except the last month) is given by disposable cash from the previous month, plus incomes less costs.

Eq. 39 represents the cash in the last month *M* (equivalent to gross margin). (**39**) is similar to (**38),** but in the last month of production the model has to pay for the used capital *UC*, with a discount rate (*ir*) accumulated for *T* years (fourth term in the RHS). The last term in RHS represents the sale of the remaining animals in the system; i.e., the animals that did not achieve slaughter weight by the end of production. In this case, to avoid distortions in the solution, a calibration parameter α is used, this was determined such that the stocking rate kept approximately constant until the end of production (for fixed demand).

Concentrate supplementation

Eqs. 40 to **46** describe the supplementation concentrate measure, i.e., steer dynamics, intake and formulation of the supplement.

Eqs. 40 and **41** are analogous to **eq. 27** and **28**, but for concentrate-supplemented steers, where FSC_m accounts for the number of steers finished under supplementation concentrate in month m; μ_{SC} is the mortality rate of steers supplemented with concentrate; SSC_m represents the number of steers selected for concentrate supplementation (from age cohort $ks=8$); SC_m is the number of steers under concentrate supplementation in month m.

Eq. 42 accounts for the beef produced under concentrate supplementation during year t (PSC_t): it is derived as the product of the number of steers times the finishing weight and carcass yield. Where γ_{SC} and ω_{SC} are the carcass yield and weight of steers finished under concentrate supplementation, respectively.

Eq. 43 represents the monthly costs of concentrate supplementation (CSC_m). The cost is proportional to the number of supplemented steers in month m (SC_m) and comprises the cost of mineral salt and urea contained in the supplement (term multiplying dmi_{SC}), where c_{urea} and c_{salt} represent the cost per kg of urea and mineral salt, respectively; dmi_{SC} is the dry matter supplement consumption ($kg.hd^{-1}.mth^{-1}$); nfc_{SC} and mc_{SC} are non-feed costs and animal maintenance costs from concentrate supplementation ($R\$.hd^{-1}.hd^{-1}.mth^{-1}$).

Eq. 44 expresses the income originating from concentrate supplemented steers (ISC_m), where pr_{SC} is the selling price of concentrated steers.

Eq. 45 accounts for the forage intake of concentrate supplemented steers in month m ($PFSC_m$), where $pdmi_{SC}$ is the grass dry matter intake of concentrate supplemented steers (in $t.hd^{-1}.mth^{-1}$).

Eq. 46 accounts for all the dry matter consumed from each crop contained in the concentrate supplement formulation in month m ($RFSC_{m,c}$), where $prr_{c,SC}$ is a dimensionless parameter that represents the proportion of crop c contained in concentrate formulation and dmi_{SC} is the concentrate dry matter intake (in $t.hd^{-1}.mth^{-1}$).

Protein supplementation

Eq. 47-54 describes the protein supplementation dynamics.

Eq. 47 represents the number of steers in the first age cohort of the category of protein supplemented steers. The number of steers for $kp=1$ in month m ($SP_{m,kp=1}$) is given by the number in $m-1$($SP_{m-1,kp=1}$) less the mortality rate (first term in the RHS), where μ_{kp} is the mortality rate for protein supplemented steers of age cohort kp, plus the animals selected to be fed by protein supplementation in month m (SSP_m, selected from ks=1), less the steers transferred to the next age cohort – after 3 months (third term in the RHS).

Eq. 48 is similar to **eq. 47** but accounts for $kp>1$. The number of steers that are changing to age cohort kp in month m (second term in RHS) is given by the number of steers selected for protein supplementation 3 months before, plus the steers selected 6 months before, 9 months before and so on $= (1-\mu_{kp=1})^3 SSP_{m-3} + (1-\mu_{kp=1})^3(1-\mu_{kp=2})^3 SSP_{m-6} + (1-\mu_{kp=1})^3(1-\mu_{kp=2})^3(1-\mu_{kp=3})^3 SSP_{m-9}$ = $\prod_{r=1}^{kp-1}(1-\mu_r)^3 SSP_{m-3(kp-1)}$. The third term in RHS is analogous but account for the number of steers that are changing from *kp* to the next age cohort *kp*+1.

Eqs. 49-53 are analogous to **eq. 42-46**, respectively. Where PSP_t is the meat produced from finished protein supplemented steers; γ_{SP} and ω_{SP} are the carcass yield and weight of finished protein supplemented steers, respectively; $SP_{m,kp}$ the number of steers under that supplementation in month *m*; CSP_m the monthly total cost of supplementing steers with protein, where $prr_{urea,SP}$, $prr_{salt,SP}$ and $prr_{NaCl,SP}$ are the proportion of urea, mineral salt and NaCl contained in protein supplement formulation, respectively; $dmi_{SP,kp}$ is the protein supplementation consumed of steers age cohort *kp* (t.hd^{-1}.mth^{-1}); nfc_{SP} and msp_{kp} are non-feed and maintenance costs for supplemented steers of age cohort *kp* (R$.hd^{-1}.mth^{-1}); pr_{kp} is selling price of steers finished under protein supplementation (note that *kp*=6 is the finishing age cohort); and $pdmi_{kp}$ is the grass dry matter intake of steers age cohort *kp*.

Nitrification inhibitors

Eq. 54 expresses the monthly costs of nitrification inhibitors ($CNIH_m$) – proportional to applied nitrogen. Let c_{NIH} be the cost of the kg nitrification inhibitor; a_{NIH} a dimensionless parameter representing application (kg of inhibitor per kg of N); *RL* is the proportion of N saved by using nitrification inhibitors (dimensionless); and $NA_{i,j}$ is the amount of N applied to convert one hectare of land use *i* to land use *j*. Thus, the double summations over *i* and *j* account for all the applied N in year *t*; LI_m (as in **Eq. 35**) is used to discount the costs in the first month for every year ($LI_m = 1$ if *m=January*, otherwise *m=0*).

GHG emissions accounting

Cattle emissions

The equations below account for direct GHG emissions from cattle by employing emissions factors.

$$ce_m = \sum_{ks} es_{ks} SS_{m,ks} + \sum_{kh} eh_{kh} SH_{m,kh} + \sum_{ks} ec_{kc} SCW_{m,kc} + e_{CV} SCV_m + e_{FL} (SF_m + FSF_m), \forall m \quad (55)$$

$$ce_{m,SC} = e_{SC} SC_m, \forall m \quad (56)$$

$$ce_{m,SP} = \sum_{kp} e_{kp} SP_{m,kp}, \forall m \quad (57)$$

Eq. 55 accounts for the greenhouse gases emissions (in CO_2e) for each cattle age cohort and feedlot steers, where ce_m is the total cattle emissions in month *m*; es_{ks}, eh_{kh}, ec_{kc} and e_{FL} are the emissions factors (in kg of CO_2e.hd^{-1}.mth^{-1}) for steers of age cohort *ks*, heifers of age cohort *kh*, cows in breeding stage *kc* and feedlot steers, respectively.

Eq. 56 and **eq. 57** account for concentrate and protein supplemented steer emissions, respectively, where e_{SC} and e_{kp} are the emissions factors (kg of $CO_2e.hd^{-1}.mth^{-1}$) of steers supplemented with concentrate and steers supplemented with protein, age cohort *kp*.

Fertilization emissions

$$fe_t = 298 cv_{N \rightarrow N_2O} \sum_j \sum_j NA_{i,j} LUC_{t(m),i,j} \quad (58)$$

$$fe_{t,NIH} = (1 - p_{NIH}) \, fe_t \quad (59)$$

Eq. 58 accounts for the emissions from nitrogen (N) based fertilizers in year *t* (fe_t). The term inside the sum gives the amount of N applied for all land use and pasture restoration options. The factor $cv_{N \rightarrow N2O}$ corresponds to the proportion of N converted into N_2O; and 298 is the N_2O equivalence in CO_2e - in global warming potential for 100 years (GWP-100).

Eq. 59 accounts for the emissions from N-based fertilizers when nitrogen inhibitors are used, where in p_{NIH} represents the efficiency of nitrification inhibitors .

Deforestation emissions

$$de_t = \frac{11}{3} \theta \left(EDA_t + DA_t \right) \quad (60)$$

Eq. 60 accounts for emissions from natural vegetation conversion into pastures in year t (de_t), where EDA_t and DA_t represent the endogenous and exogenous deforested area. Emissions are given by the product of the deforested area multiplied by biomass above ground coefficient, θ (in carbon per unit of area), converted to CO_2e by multiplying by 11/3.

Pasture emissions and carbon sequestration

The equations below describe the pasture soil carbon dynamics.

$$cs_{t,p} = cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} RPA_{t,p} + \\ + \Delta cs_{t,p} \;, \forall t,\, p \neq \mathrm{C} \tag{61}$$

$$\Delta cs_{t,p} = r\left(\varepsilon_p - \left(cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \\ - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} RPA_{t,p} \right) \right) LU_{t,p} \\ \forall t,\, p \neq \mathrm{C} \tag{62}$$

$$cs_{t,p} = cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} RPA_{t,p} + \\ + \sigma\left(EDA_t + DA_t\right) + \Delta cs_{t,p} \;, \forall t,\, p = \mathrm{C} \tag{63}$$

$$\varDelta cs_{t,p} = r\left(\varepsilon_p - \left(cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i}\right) - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} LUC_{t,p} + \sigma\left(EDA_t + DA_t\right)\right)\right) LU_{t,p}$$

$$\forall t,\, p = \mathrm{C}$$

(64)

$$cs_{t,c} = \sum_i \frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,c} + r\left(\varepsilon_c - \sum_i \frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,c}\right) LU_{t,c}$$

$$\forall t, \forall c$$

(65)

Eq. 61 describes the soil carbon accumulation for pastures levels except pasture *p=C*.

The amount of stocked carbon under pasture *p* in year *t* ($cs_{t,p}$) (in tonnes of carbon) is given by the carbon transferred from pasture *p-1* (degradation) or the carbon transferred from pasture *p* itself, if no degradation occurs (first term in the RHS), as in **Eq. 3**. The second term in the RHS represents the transferred carbon from/to any other pasture or crops according to the land use change decision variables. We assume a proportional transfer of carbon per area of converted land use, e.g., if 100 ha of pasture *F* is restored to pasture *A* in year *t*, then the carbon in *F* has to be proportionally transferred to *A*, i.e., the amount of carbon per unit of area in *F* in *t-1* $\left(\frac{cs_{t-1,F}}{LU_{t-1,F}}\right)$ multiplied by $LUC_{t,F,A}$ = 100 ha is transferred to pasture *A*. The second term inside the sum is analogous but accounts for the carbon that is transferred from pasture p to other improved pasture or crops. The third term in RHS is responsible for removing carbon when pasture area ($RPA_{t,p}$) is removed from pasture level p in year t. The last term on the RHS represents the carbon sequestration rate.

Eq. 62 describes the carbon sequestration rate under pasture p in year t ($\Delta cs_{t,p}$), it is calculated as a function of the difference of the current carbon stock from the carbon equilibrium value of pasture p (ε_p) (in t.ha^{-1}) . The parameter r represents the carbon losses by plant respiration and determines the speed in which equilibrium is reached. For simplicity, **Eq. 62** can be written as $\Delta cs_{t,p} = r(\varepsilon_p - \varphi_{t,p})LU_{t,p}$, where:

$$\varphi_{t,p} = cs_{t-1,p-\delta(t)} + \sum_i \left(\frac{cs_{t-1,i}}{LU_{t-1,i}} LUC_{t,i,p} - \frac{cs_{t-1,p-\delta(t)}}{LU_{t-1,p-\delta(t)}} LUC_{t,p-\delta(t),i} \right) - \frac{cs_{t-1,p-\delta(t)}}{LU_{t,p-\delta(t)}} RPA_{t,p} \quad (62b)$$

Eq. 62b represents the carbon stocks in pasture p in year t just before carbon sequestration occurs, i.e., the amount of carbon transferred to pasture p in year t from pasture p in t-1 or other land uses.

Eq. 63 and **64** are analogous to **Eq. 61** and **62,** respectively**,** but since for $p=C$ there is area converted from natural vegetation (EDA_t+DA_t), the carbon (assumed in equilibrium) from natural vegetation has to be transferred to pasture C as well (fourth term in the RHS of **Eq. 63**), where σ represents the soil organic carbon in equilibrium of natural vegetation (t.ha^{-1}).

Eq. 65 accounts for the soil organic carbon under crops ($cs_{t,c}$). As crops have to be planted every year, the stocked carbon is given by the transferred carbon from the previous land use, plus the sequestration rate. Analogous to the pasture sequestration rate, it is calculated as the difference between the current stock and equilibrium (ε_c), multiplied by the plant carbon respiratory losses.

Calculation of restoration and land use change costs

We assume the cost – and therefore inputs - necessary to change from *X* to *Y*, where *X* and *Y* can be any element in *LU = {A, B, C, D, E, F, Corn(silage), Corn(grain), Soybeans}* is given by:

Cost(X,Y) = Cost(F,Y) – Cost(F,X)

The *Cost(F,Y)*, and the description and amount of inputs, for any *Y* in *LU* is presented in Table S3-S7.

In the case where *X = Y*, "the cost to restore from *X* to *X*", represents the cost of maintaining the DMP X, i.e., avoiding degradation. The amount of input and cost to keep any DMP level is described in Table S4.

The inputs used for the pasture restoration and plantation of corn and soybeans followed recommendations in Sousa et al. (2004) and Tomé Junior (1997). Machinery and services were added following technical recommendations established by Agronomists (MSc. Paulo Roberto Albertini and Dr. Luis Gustavo Barioni, Personal Communication, Campinas, 2013) and by Veterinary (Dr. Tiago Zanett Albertini, Personal Communication, Campinas, 2013), with expertise in livestock and crop systems of production in the *Cerrado* biome. Further, item prices were based on time series collected from the Institute of Agricultural Economics (IEA, 2012) and were deflated to the 2012 value using IGP-DI (FGV, 2012).

Model calibration

This section describes the process used to obtain the pasture Average Dry Matter Productivity (ADMP) from 2006, as used in the construction of the baseline scenario (section 2.5). The land use changes dynamically as a function of time (composition of the total land across the pastures types and crops), as well as the herd dynamic (composition of animals age cohorts). However, after several years, the solution tends to reach equilibrium; i.e., land and herd composition tends to present similar values throughout the simulation. To obtain the ADMP for 2006, we ran the model with the 2006 pasture area and beef demand constant for 25 years of simulation. As the solution stabilized, we calculated the ADMP as a function of the composition of pasture types for the stabilized solution and the values of DMP in Table 1, obtaining the value of 10 t-DM.ha^{-1}.yr^{-1}.

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